

# LYMAN ALPHA FOREST TOWARDS B2 1225+317

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## ABSTRACT

We present observations of the Lyman alpha forest towards B2 1225+317 taken at a resolution of  $18 \text{ km s}^{-1}$ . A clean sample of Lyman alpha forest lines is extracted after a careful profile fitting analysis and removal of absorption lines of heavy elements. The sample is analyzed for statistical properties. Eighty percent of the column densities are  $< 10^{14} \text{ cm}^{-2}$ . A single power law is inconsistent with the column density distribution and a steepening/break in the distribution is indicated. The average velocity dispersion parameter is  $29.4 \text{ km s}^{-1}$ . We find  $3\sigma$  evidence for a correlation between column density and the velocity dispersion parameter. The correlation, however, is mainly due to narrow lines and weakens to  $1.2\sigma$  if lines with velocity dispersion parameter smaller than  $20 \text{ km s}^{-1}$  are excluded. An excess of line pairs with velocity separation  $\leq 100 \text{ km s}^{-1}$  over the expected number is found.

**Key words:** intergalactic medium – quasars: absorption lines – quasars: individual: B2 1225+317

## 1 INTRODUCTION

Lyman alpha forest lines in the spectra of QSOs are generally believed to be produced by intergalactic clouds (Sargent et al 1980), though some evidence exists for their being associated with galaxies (Lanzetta et al 1995; Le Brun et al, 1996; Bowen et al 1996). An understanding of the properties of these lines is crucial not only for the understanding of their nature, but also for the understanding of the formation and evolution of structure in the Universe as well as that of the physical conditions existing in the universe at redshifts up to 5. These lines are in fact the only available probes of the intergalactic medium in the Universe at these times. A large amount of observational data for these lines, taken at intermediate resolution ( $\text{FWHM} \simeq 1.0 \text{ \AA}$ ), have been compiled over the years. Because the Lyman alpha lines are numerous, line blending in the intermediate resolution data poses a severe handicap. It is therefore necessary to have high resolution observations of these lines to understand their true properties such as the column density, velocity dispersion distributions and clustering. Such data are becoming available and to date observations are available for about 15 quasars at resolutions ranging from  $6 \text{ km}$

$\text{s}^{-1}$  to  $35 \text{ km s}^{-1}$ . These observations have already provided interesting information about the Lyman alpha forest lines. The lines are found to be clustered on scales of up to  $300 \text{ km s}^{-1}$ . The column density distribution is found to have a break at  $N_{\text{H I}} \sim 10^{14} \text{ km s}^{-1}$ . Most importantly some lines have been found to have velocity dispersion parameters smaller than  $20 \text{ km s}^{-1}$  (Pettini et al 1990, Srianand and Khare 1994, Kulkarni et al 1996 etc). Since these properties are statistical in nature, more data is always welcome to get a better understanding of the line properties.

This paper presents new observations of Lyman alpha forest lines towards B2 1225+317 at a resolution of  $18 \text{ km s}^{-1}$  with signal to noise ratio larger than 10. We have analyzed the data by profile fitting the observed lines. Heavy element lines are carefully searched and removed. The statistical properties of the clean sample of Lyman alpha forest lines are studied. In section 2, we present details of the observations; in section 3, we describe the profile fitting procedure. In section 4, we discuss the details of the heavy element line systems reported in the literature for this QSO as well as the results of the profile fitting analysis for heavy element lines belonging to these systems that fall in our observed

range. In section 5, we present the results of our analysis of the statistical properties of these lines. This is followed by conclusions in section 6.

## 2 OBSERVATIONS

The near UV observations of B2 1225+317 were obtained on the nights of 23 and 26 March, 1987, with the Kitt Peak Mayall 4-meter telescope plus echelle spectrograph. The instrumental configuration included the 58.5 l/mm 63 deg echelle grating with the blaze peak centered on the format. The 226-1 cross-disperser grating was used in second order through a copper sulfate filter to allow coverage of orders 96 through 65, or 3130 to 4500 Å. The poor seeing on both nights of 3 - 4" FWHM and the intermittent clouds on the second night imposed a substantial throughput penalty to maintain the resolution through the 1 arcsecond slit. A decker masked the slit to a height of 10 arcseconds, necessary for separating the orders at their closest spacing at the violet end of the echellogram. The spectrograph was rotated between the 3000-second exposures to orient the slit approximately along the parallactic angle to avoid selective losses in the far UV. Each object exposure was preceded and followed by Th-A argon arc lamp images for interpolation of the wavelength solution. The total exposure time on the quasar was 392 minutes on 23 March and 342 minutes on 26 March.

The spectrograph output was coupled through the "UV Fast" camera to the Intensified CCD Detector. That detector consisted of an RCA two-stage magnetically focused "Carnegie" image tube with a 38 mm cathode, lens coupled to the "TI3" CCD. The DQE of the photocathode has a flat peak at about 18% from 3500 to 4500 Å; the efficiency of the cross-disperser grating falls rapidly longward of 4000 Å, however, giving reduced S/N in the redder orders. For calculation of the S/N, a system gain of 20 data numbers per detected photon was assumed, corresponding to about 80 electrons at the CCD for each output phosphor scintillation. The agreement with the S/N ratio derived from local continuum intervals suggests that this value for the gain is a good estimate. The slit afforded 17 km s<sup>-1</sup> resolution FWHM as measured in single Th-A arc exposures; the final combined image from the entire night shows 18 km s<sup>-1</sup> resolution, as measured from a combination of all the arc exposures, rebinned identically to the quasar spectra. The resolution was limited essentially by the sampling of the slit profile with 2 15-micron pixels; the magnification of the transfer lens between the image tube and CCD was a factor of 1.66. Because of the substantial photon gain, the detector works nearly as a photon counter, in that the CCD read noise is negligible; exceptions are the significant defects in the TI3 chip and the fact that ion events are fully amplified in the integrated image.

## 3 FITTING PROCEDURE

The profile fitting algorithm and analysis are similar to those described by Kulkarni et al. (1996), except that we also use  $\chi^2$  per degree of freedom as a measure of goodness of fit as used by several authors (Rauch et al. 1992, Christiani et

al. 1995).  $\chi^2$  and rms values were calculated over parts of the spectrum free of absorption lines. While considering the goodness of a profile fit for a line, we used the values of rms and  $\chi^2$  calculated in the line free regions extending up to 10 Å on either side of the line. The minimum number of components necessary to give values of  $\chi^2$  per degree of freedom and rms residual consistent with these values were used in the fit of each line. Prior to 1990, ten heavy element line redshift systems had been reported in the literature for this QSO (York et al 1991). Three additional systems were found by Steidel and Sargent (1992). Using a search list similar to that used by Hunstead et al (1986), PK and RS generated a list of heavy element lines belonging to these systems that would be present in our spectra. Independently, using an expanded list based on Morton, York and Jenkins (1988), compiled by DW, DGY made a similar list of lines of heavy elements that contaminate the lines of the forest. Each system was analyzed carefully by looking for wavelength consistency as well as the consistency of line strength for doublet or multiplet lines of the same species. Details of the heavy element line systems present and the heavy element lines identified in each of them are given in next section. Detailed profile fitting and deblending of Ly  $\alpha$  lines, as described by Kulkarni et al (1996), was possible only for system A, which was studied in detail earlier by Bechtold, Green and York (1987); for system H, for which the Mg II doublet is present in our data; and for system I and J, for which C IV lines are available. For most other systems no lines were found outside the Ly  $\alpha$  forest in our spectra and no multiplets were found inside the Ly  $\alpha$  forest which complied with the consistency tests mentioned above. In some cases, lines were present only at the expected positions of O I(1304) and C II(1331) lines. As they are single lines and no other lines belonging to these systems were present outside the forest, and as the Ly  $\alpha$  lines for these systems, whenever present, are saturated, it was not possible to deblend any Ly  $\alpha$  forest lines from these lines. We fitted them as Ly  $\alpha$  lines. Note that none of these lines are included in our sample of lines defined below. The spectrum along with the fitted profiles is presented in figure 1. The line positions are tick marked in the figure. For the Ly  $\alpha$  lines thus compiled we used a computer programme described by Srianand & Khare (1994) to search for new heavy element line systems. We do not detect any new systems.

The list of all lines studied is given in Table 1, which lists  $\lambda$ ;  $\log N_X$  for species 'X' noted in the last column; the Doppler parameter,  $b$ , for the profile fits; and the redshift of the line. The notations after the line wavelength, in column 1, are "b", line has unusual profile due to either bad pixel e.g.  $\lambda 3392\text{\AA}$ ,  $\lambda 3338\text{\AA}$  etc, or line is broad and/or noisy and it's reality is not certain e.g.  $\lambda 3382\text{\AA}$ ; this selection criterion is subjective to some extent, however, two of us (PK and RS) independently arrived at the same set of lines which fall in this category; "d", line deblended from heavy element line; and "s", evidently, a single component (a fact used later in this paper). Part of the spectrum with wavelength smaller than 3400 Å has S/N value between 2 and 10 while the part with wavelength larger than 3400 Å has S/N value between 10 and 20. The completeness limit for our data was determined by calculating the minimum necessary column density,  $N_{HI}$ , for a given value of the velocity dispersion parameter such that the line will be detected at the 5  $\sigma$

level for rms error of 10 % ( which is the upper limit to the rms for  $\lambda > 3400\text{\AA}$ ). These values are plotted in figure 2 as a continuous line. It can be seen that lines with  $b < 100 \text{ km s}^{-1}$  could be detected in our spectra (with  $\lambda > 3400\text{\AA}$ ) for  $\log N_{\text{HI}} \text{ cm}^{-2} > 13.2$ . For statistical analysis we have, therefore, compiled a sample, S1, of lines having  $\log N_{\text{HI}} \text{ cm}^{-2} > 13.2$  and  $\lambda > 3400\text{\AA}$ , excluding lines within 8 Mpc from the QSO and lines with unusual profiles (marked with 'b', hereafter LWUPs). The lines included in S1 are marked with a \* in Table 1. Lines marked with '?' are the LWUPs, which otherwise satisfy the criterion for inclusion in the Lyman alpha sample. These lines along with S1 form our extended sample S2.

#### 4 INFORMATION ABOUT HEAVY ELEMENT LINE SYSTEMS

##### System A : ( $z = 1.79$ )

This system has been studied in high resolution ( $\sim 10 \text{ km s}^{-1}$ ) by York et al. (1984) and by Bechtold, Green and York (1987). They observed C IV, Fe II, Mg II and Si II lines which were fitted with up to 12 components with redshifts in the range 1.7933-1.7975. Our spectrum covers 1136 - 1435  $\text{\AA}$  in the rest frame of the system. The Si II 1190, 1193 and Ly  $\alpha$  lines are distorted due to pixel defects or cosmic ray hits. These deleterious effects prohibit deblending of Lyman alpha lines from the Si II lines. The main Lyman alpha line is too saturated to allow fitting of the components seen in the heavy element lines at these redshifts. Detailed photoionization modeling for this system has been considered by Bechtold, Green and York (1987). We are able to fit most lines with 7 components with redshifts close to the redshifts obtained by Bechtold, Green and York (1987).

##### System B: ( $z = 1.6251$ )

Wilkerson et al. (1978) observed C IV, Si IV, C II, Si II and Ly  $\alpha$  lines belonging to this system. Mg II lines were not detected by Steidel and Sargent (1992). Young, Sargent & Boksenberg (1982) detected C IV lines. Our spectrum covers 1211 - 1530  $\text{\AA}$  in the rest frame of this system. A line is present at the expected position of Si IV 1402. However no line is observed at the expected position of 1393. Based on the upper limits from the absence of this line, we conclude that the line at the position of Si IV 1402 is a Ly  $\alpha$  forest line and any Si IV line if present can not alter the deduced parameters of this Ly  $\alpha$  line significantly. Si II (1260) and C II (1334) lines are possibly present. In our low quality data near 3180  $\text{\AA}$  (not shown here), we find Si III  $\lambda 1206$  ( $W_\lambda = 0.92 \pm 0.15 \text{\AA}$ ,  $1 \sigma$ ) and Lyman alpha ( $W_\lambda = 3.94 \pm 0.23 \text{\AA}$ ). No other heavy element lines are present. As Mg II and Fe II lines have not been observed for this system, the reality of C II and Si II lines is doubtful. Also the Ly  $\alpha$  line lies in very low S/N region. We have therefore not attempted to deblend any Ly  $\alpha$  lines from these lines, but have excluded these lines from Ly  $\alpha$  line sample.

##### System C: ( $z = 1.8865$ )

Young, Sargent and Boksenberg (1982) detected only C IV lines belonging to this system. The displayed spectrum covers 1101-1391  $\text{\AA}$  in the rest frame of this system. Si IV is not present in our spectrum at slightly longer wavelength than the region discussed here. We find the Ly  $\alpha$  line belonging to this system. This can be fitted with 5 components, the

redshifts of which differ slightly from the values quoted by Steidel & Sargent (1992). Lines of O I and C II are possibly present. These lines are removed from our Ly  $\alpha$  line sample. No other heavy element line is found for this system. We note that the profile of the shortward wing of the Lyman alpha is fit by a damped profile, with  $N_{\text{HI}} = 2.5 \times 10^{17} \text{ cm}^{-2}$ . The clean wing yields an upper limit for deuterium,  $N_{\text{DI}} \leq 1.6 \times 10^{13}$ , giving,  $N_{\text{DI}}/N_{\text{HI}} \leq 6.4 \times 10^{-5}$ .

##### System D: ( $z = 1.8963$ )

Wilkerson et al. (1978) detected Ly  $\alpha$  and C IV lines for this system. Young, Sargent and Boksenberg (1982) reported the detection of C IV lines alone. Our spectrum covers 1098 -1386  $\text{\AA}$  in the rest frame of this system. We find Ly  $\alpha$  line belonging to this system: this line is blended with Si II (1260) of system A. The H I portion is fitted with 3 components, the redshifts of which differ slightly from the values quoted by Steidel & Sargent (1992). Components of C II are possibly present. These lines are excluded from our Ly  $\alpha$  line sample. No other heavy element line is found for this system.

##### System E: ( $z = 2.1103$ )

This system was reported by Wilkerson et al (1978). However the system is doubtful as Ly  $\alpha$  is very weak. Young, Sargent and Boksenberg (1982) and Steidel and Sargent (1992) did not identify this system. Our spectrum covers 1022 - 1291  $\text{\AA}$  in the rest frame of this system. We also do not find any line belonging to this system and thus conclude that this system is not real.

##### System F: ( $z = 1.3582$ )

Wilkerson et al. (1978) found only marginal evidence for the presence of this system. Steidel & Sargent (1992) did not find Mg II for this system. They also reported the absence of this system in their unpublished high resolution data. Our spectrum covers 1348 - 1702  $\text{\AA}$  in the rest frame of this system. We do not find C IV lines with proper redshift matching and line strengths. No other heavy element lines are detected. Thus we conclude that this system is not real. We note, however, that the first three lines in Table 1 could be Si IV  $\lambda 1393$ . Matching components for Si IV  $\lambda 1402$  are present. It is unusual to find Si IV without C IV (but see Khare, York and Green 1989).

##### System G: ( $z = 2.1197$ )

Wilkerson et al (1978) found Ly  $\alpha$ , Ly  $\beta$ , N I, C IV and O VI lines belonging to this system. Young, Sargent and Boksenberg (1982) found weak C IV doublet. Our spectrum covers 1019 - 1287  $\text{\AA}$  in the rest frame of this system. We identify Ly  $\alpha$ , Ly  $\beta$  and possibly N V lines. Other heavy element lines are not present. In particular the N I lines suggested earlier are definitely not present, being confused with nearby Lyman alpha lines and a possible line of C II from another system.

##### System H: ( $z = 0.363$ )

This system was reported in Steidel and Sargent (1992) based on their unpublished high resolution data. Our spectrum covers 2332 -2934  $\text{\AA}$  in the rest frame of this system. We identify the Mg II doublet, and deblend the associated Lyman alpha lines. Mg I is probably present and Fe II  $\lambda 2600$  is possible, but the feature does not match the Mg II profile well.

##### System I: ( $z = 1.2252$ )

This system with two components was reported in Steidel and Sargent (1992) based on their unpublished high resolution data. However, they did not find Mg II, Mg I and Fe

II lines belonging to this system. Our spectrum covers 1429 - 1804 Å in the rest frame of this system. We identify only a weak C IV doublet belonging to this system. Lyman alpha lines are separable at our resolution, but are situated so as to have simulated a stronger, more complex profile, in data of slightly lower resolution.

#### System J: ( $z = 1.4290$ )

This system was reported in Steidel and Sargent (1992) based on their unpublished high resolution data. They did not find Mg II, Mg I and Fe II lines belonging to this system. Our spectrum covers 1309 - 1653 Å in the rest frame of this system. We identify only a C IV doublet belonging to this system. Si IV is absent.

## 5 RESULTS OF STATISTICAL ANALYSIS

### 5.1 $N_{\text{HI}}$ distribution

Our sample contains single lines and lines fitted with multiple components as well as lines deblended from heavy element lines. It is possible that the deblending procedure may not be ideal and might artificially introduce some bias in the derived line parameters in the data. In order to check this possibility we performed several KS tests. The probability that the column densities for the set of lines which were fitted with single components and the set of lines which were fitted with multiple components belong to the same parent population is  $\sim 0.18$ . This indicates that the fitting procedure does not introduce any bias in the  $N_{\text{HI}}$  distribution. The probability that  $N_{\text{HI}}$  values for lines lying in the region of the spectrum with  $S/N > 10$  and  $S/N < 10$  are drawn from the same parent population is 0.86 indicating that the  $S/N$  does not affect the column density estimates significantly.

All the Ly  $\alpha$  lines in our list have column density between  $5 \times 10^{12}$  and  $1.2 \times 10^{15} \text{ cm}^{-2}$ . We performed maximum likelihood analysis, for sample S1, to determine the index,  $\beta$ , of the assumed power law column density distribution. The resulting values of  $\beta$  for various lower limiting column densities,  $N_{\text{HI}}^{\text{min}}$  along with the Kalmogoroff Smirnov (KS) probability,  $P_{\text{KS}}$ , that the observed distributions are well represented by the power law are given in Table 2. The probability is only 0.088 for  $\log N_{\text{HI}}^{\text{min}} \geq 13.2$ , indicating that a single power law does not provide an acceptable description of the observed column density distribution. A single powerlaw does provide a good fit for lines with  $\log N_{\text{HI}}^{\text{min}} \geq 13.4$ . The values of  $\beta$  and  $P_{\text{KS}}$ , however, increase with increase in the minimum column density cutoff, which is consistent with the steepening of the power law at high column densities as suggested by Petitjean et al (1993) and Kulkarni et al (1996). The values of  $\beta$  for S2 are also very similar to those in Table 2.

Large samples are always better for determining the statistical properties. We have combined the lines towards Q1331+170 (sample S2 of Kulkarni et al.1996, which were observed with the same resolution, have similar  $S/N$  and cover similar redshift range as our sample), towards 1101-26 (Carswell et al 1991) and towards 2206-199 (Rauch et al 1993) with our sample S1. The last two QSOs have been observed with somewhat different resolution but cover similar redshift range. The results of maximum likelihood analysis for this extended sample are also given in Table 2. The extended sample has the KS probability of 0.039 for  $\log N_{\text{HI}}^{\text{min}}$

$=13.2$ , indicating that a single power law does not give an acceptable description of the data. A change in the slope of column density distribution with column density is also indicated. Rauch et al (1992) showed in the case of Q0014+813 that a single power law describes the data well with  $P_{\text{KS}} = 0.51$ . Giallongo et al (1993), considering only lines in the spectra of Q2126-158, got  $P_{\text{KS}} = 0.43$  for a single powerlaw fit. However, when lines from these QSOs were combined with lines from 1101-264, Giallongo et al (1993) showed that a single powerlaw is acceptable with a probability of only 0.02. They reported this as a signature for the break in the power law distribution. Cristiani et al (1995) showed for Q0055-269 that the probability for a single power law distribution is 0.0007. They attributed the difference in significance from Giallongo et al's results for Q2126-158 to the small number of lines in that sample compared with that for Q0055-269. Recently Giallongo et al (1996) have confirmed the break with an extended high resolution sample. They suggest that the line blanketing effect due to the high column density lines that conceals weak lines, though appreciable at high redshifts, may not be the cause for the observed break. We have performed a double power law fit to our extended sample. The column density distribution along with the power law fits are shown in figure 3. The slopes of the power laws for  $N_{\text{HI}} \leq 14.0$  and  $N_{\text{HI}} \geq 14.0$  being -1.15 and -2.05 respectively. Giallongo et al (1996), for 1100 Lyman alpha lines in the redshift range 2.8-4.1 have obtained the values for the corresponding slopes to be -1.4 and -1.8, which are somewhat different than our values.

Thus either, as suggested by Cristiani et al (1995), there exists a column density cutoff at about  $10^{14} \text{ cm}^{-2}$  and the higher column density lines are blends of weaker lines which could not be deblended due to the finiteness of the resolution and signal to noise or the break in the column density distribution is due to some physical process. Hu et al (1995) also find a steepening of the powerlaw beyond the column density of  $3 \times 10^{14} \text{ cm}^{-2}$ , in their high resolution and very high  $S/N$  KECK data. It, thus appears that the steepening of the column density distribution may be due to some physical effect. In the frame work of the structure formation models, the break may be a consequence of the onset of Jean's instability (Meiksin and Madau 1993). While the higher column densities are due to virialized objects, the lower column density clouds may just reflect the density fluctuations in the intergalactic medium (Miralda-Escude & Rees, 1993). The steeper slope obtained for stronger lines for our sample compared to the slope obtained by Giallongo et al (1996) for similar lines at higher redshift is consistent with this picture. The break could possibly be the result of the presence of two populations of the Lyman alpha clouds as suggested by the KECK observations. While the high column density lines may be associated with galaxies the lower column densities may come from truly intergalactic clouds.

If the break in the column density distribution is real and if the number density evolution index  $\gamma$  increases with an increase in column density (Srianand & Khare 1994), then one would expect to see the break more prominently in low redshift samples. More high resolution, profile-fitted data are required to confirm the existence and the redshift dependence of the break. If the break is real, it will occur at lower column densities in the vicinity of QSOs due proximity effect and one should see a change in the column density

distribution in the vicinity of the QSOs. Existing high resolution data however do not show any such change (Srianand & Khare, 1996).

## 5.2 b-distribution

The Lyman  $\alpha$  lines have  $b$  values ranging from 5 to 80 km s<sup>-1</sup>. A histogram of  $b$ -values for S1 is plotted in figure 4. We have also plotted the histogram for LWUPs and for all the lines with  $\lambda \geq 3400\text{\AA}$  without any column density cutoff but excluding the LWUPs. It can be seen that the lines with column density smaller than  $10^{13.2}\text{cm}^{-2}$  have  $b$  values smaller than the stronger lines, which indicates a correlation between the column density and  $b$ ; it may also be due to the incompleteness of the sample for column densities smaller than  $10^{13.2}\text{cm}^{-2}$ . This will be discussed further in the next section. Also the LWUPs have  $b$  values which are larger than the rest of the lines. The KS probability that these lines are drawn from the same parent population as the rest of the lines is only  $2 \times 10^{-7}$ . The mean and median values for sample S1 are  $29.4 \pm 7.9$  and  $27.66$  km s<sup>-1</sup> respectively. The mean and median values for sample S2 are  $32.1 \pm 9.7$  and  $30.6$  km s<sup>-1</sup> respectively. The mean and median values for lines in S1, which are fitted with single components are  $27.4 \pm 6.9$  and  $27.3$  km s<sup>-1</sup> respectively, very close to the values for the whole sample. KS test shows that the probability that the  $b$  values of lines fitted with single components and lines fitted with multiple components are taken from the same parent population is 0.65. Thus the fitting procedure does not introduce any artificial bias in the  $b$ -value distribution. The average  $b$ -value is similar for regions of spectra with  $S/N > 10$  and  $S/N < 10$  and for the lines deblended from heavy element lines ( $28.6 \pm 6.1$ ). The KS test shows that the probability that the  $b$ -values for regions of spectra with  $S/N < 10$  and  $S/N > 10$  are taken from the same parent population is 0.53. The probability that the  $b$ -distribution of lines in B2 1225+317 and in Q1331+170 are drawn from the same parent population is 0.97.

There is a considerable debate in the literature over the temperature of Ly  $\alpha$  clouds. Pettini et al. (1990) found most  $b$ -values for lines in the spectra of Q2206-199N to be smaller than 22 km s<sup>-1</sup> and suggested that Ly  $\alpha$  clouds are cool having a temperature between 5000 and 10,000 K. This conclusion was however contradicted by Carswell et al. (1991) who found an average  $b$ -value of 30 km s<sup>-1</sup> for Q1101-264. Average  $b$ -values found for various QSOs studied at high resolution vary between 27-34 km s<sup>-1</sup> (Fan and Tytler 1994, Cristiani et al 1995, Kulkarni et al. 1996). Rauch et al (1993), using simulated spectra, showed that some of the narrow ( $b \leq 15$  km s<sup>-1</sup>) lines could arise artificially in the spectra due to noise. They suggested that probably all the narrow lines could be accounted for by such artificial lines and some unidentified heavy element lines. Recently Lu et al (1996) have reached the same conclusion. They found a lower limit of 15 km s<sup>-1</sup> to the  $b$  values in their data for Q0000-26. Hu et al (1995) have been able to identify most of the lines with  $b < 20$  km s<sup>-1</sup> with metal lines and therefore propose a cutoff value of 20 km s<sup>-1</sup>. Giallongo et al (1996), however, find that about 15% of the lines in their sample have  $b$  values between 10 - 20 km s<sup>-1</sup>.

In our sample  $\sim 19\%$  of the lines have  $b$ -values smaller than 20 km s<sup>-1</sup>. We have not been able to identify these

lines as heavy element lines. 24% of the lines fitted with single components have  $b$ -value  $< 20$  km s<sup>-1</sup> while 16% of the lines fitted with multiple components or deblended from heavy element lines have  $b < 20$  km s<sup>-1</sup>. As noted above, low column density lines show low  $b$ -values more often compared to high column density lines. While 44% of the lines in our sample with  $\log N_{\text{HI}} < 13.5$  have  $b$ -value  $\leq 20$  km s<sup>-1</sup>, only 8% of the lines with  $\log N_{\text{HI}} > 13.5$  have  $b$ -value  $\leq 20$  km s<sup>-1</sup>. This is consistent with the results for other QSOs (Fan & Tytler, 1994). Another interesting point to note is that if we consider only clean lines which are fitted with single components there is no line with  $b < 20$  km s<sup>-1</sup> for  $\log N_{\text{HI}} > 13.5$ . A similar trend is noted by Giallongo et al. (1993), who concluded that either such lines are really absent or they are systematically hidden in blends, corresponding to a cloud temperature of 24000 K.

An upper limit of 55 km s<sup>-1</sup> to the  $b$ -value for thermally stable clouds has been obtained by Donahue and Shull (1991). Press and Rybicki (1993) have pointed out that the high  $b$ -values can not be thermal as otherwise the baryon density contributed by the Ly  $\alpha$  clouds will exceed the upper limit given by the big bang nucleosynthesis. Note that the  $b$ -values for sample S1 are mostly smaller than 50 km s<sup>-1</sup>.

Above results indicate the presence of some correlation between  $b$ -value and the column density, which we discuss in detail in the following section, or that the stronger lines are unresolved blends of lower column density components with smaller  $b$ -values.

## 5.3 $N_{\text{HI}}$ - $b$ correlation

There is a considerable controversy over the presence of a correlation between  $N_{\text{HI}}$  and  $b$ . Pettini et al (1990) showed a clear correlation in the case of Ly  $\alpha$  lines observed in the spectra of Q2206-199. They considered only unsaturated unblended lines for the profile fitting and did not put any completeness limit on  $N_{\text{HI}}$ . This was questioned by Carswell et al (1991) who using a similar observational setup found no correlation in the case of Q1101-264. Rauch et al (1993) reanalyzed the Q2206-199 spectra and showed that the apparent correlation of Doppler parameter and column density can be accounted for entirely by biases in the line finding and fitting procedure due to the finite signal to noise. Invariably all the spectra show this correlation when the completeness limit to the column density is not applied. Complete column density limited samples usually do not show a clear correlation (Rauch et al. 1992, Kulkarni et al 1996. etc). Recently Savaglio et al (1996) have shown that at least some of the  $N_{\text{HI}}$  vs.  $b$  correlation may result from the fact that strong Lyman alpha lines are blends of weaker lines which get identified only when a simultaneous fit to the Lyman alpha and Lyman beta lines is performed.  $N_{\text{HI}}$  vs.  $b$  plot for our sample is given in figure 2. The figure also shows the  $5\sigma$  completeness limit for our sample, which was calculated as described in section 3.

The results presented in the last section indicate the presence of correlation in our data. Spearman rank correlation test applied to the whole data without any cutoffs but excluding lines within 8 Mpc of the QSO shows a  $3.62 \sigma$  correlation with the chance probability of only  $2.2 \times 10^{-4}$ . Excluding the LWUPs increases the correlation to  $5.5 \sigma$  level.

Sample S1 shows a  $3.12 \sigma$  correlation with chance probability of  $1.1 \times 10^{-3}$ , while S2 shows a  $2.03 \sigma$  correlation with chance probability of 0.04. The correlation for sample S1 reduces to  $1.25 \sigma$  level if we exclude lines with velocity dispersion parameter below  $20 \text{ km s}^{-1}$ . When we consider only clean lines which are fitted with single components (marked 's' in Table 1, similar to Pettini et al criteria), with  $\log N_{\text{HI}} > 13.2$ , there is a  $2.83 \sigma$  correlation with chance probability  $2 \times 10^{-3}$ .

We thus confirm the findings of Hu et al (1995) that the correlation between the column density and velocity dispersion parameter crucially depends on the presence of Ly  $\alpha$  lines with  $b$  values smaller than  $20 \text{ km s}^{-1}$ . We have not been able to identify these lines with any heavy element lines. If these lines are indeed heavy element lines or have arisen artificially due to the noise then the correlation can be ruled out. If Ly  $\alpha$  lines with small  $b$  values do belong to the forest then the correlation is present but the strength does depend on the criterion used for selecting the line sample. Our exclusion of LWUPs from the sample increases the strength of the correlation from  $2.03$  to  $3.12 \sigma$  level. The correlation found by Pettini et al (1990) can also be understood as being due to this effect.

#### 5.4 Clustering properties of Ly $\alpha$ clouds

The pair velocity correlation between Ly  $\alpha$  clouds along the line of sight has been one of the tools commonly used to study the clustering properties of Ly  $\alpha$  clouds (Sargent et al. 1980). Webb (1987) showed, in the case of Ly  $\alpha$  absorption lines obtained with high resolution spectroscopy, that there is an excess in the pair velocity correlation on scales  $\sim 300 \text{ km s}^{-1}$ . There are claims and counter claims for the detection of excess on small velocity scales using high resolution data samples. (Srianand & Khare 1994, Kulkarni et al 1996, Rauch et al 1992, Pettini et al 1990 etc).

We studied the pair velocity correlation in our extended data. Sargent et al (1980) used a ramp-shaped function in order to account for the limited redshift coverage of each spectra. Instead of taking any correction function, we calculated the expected number of lines in various velocity bins taking into account the observable range in the particular spectra for each Ly  $\alpha$  line. The observed number of pairs in each velocity bin with the expected number and their  $2 \sigma$  (root  $N$ ) errors are plotted in figure 5 for two different values of column density cutoffs. There is a clear excess on the velocity scales  $50 - 100 \text{ km s}^{-1}$ , the distribution being consistent with the expected distribution for larger velocity intervals. Note that the deficit in the first bin is the artifact of blending due to finiteness of resolution. As the correlation function decreases steeply at high velocity intervals one requires more data to reduce the random noise in the correlation function, in order to detect the small amplitude on these velocity intervals. The values of  $\xi$  are  $1.35 \pm 0.42$  and  $3.14 \pm 1.19$  for lines with  $\log N_{\text{HI}} \geq 13.2$  and  $\geq 13.7$  respectively. Dependence of the clustering amplitude on the strength of the lines in our data is consistent with the results of Cristiani et al (1995) and Srianand (1996). From the study of 1100 lines in the redshift interval 2.8-4.1 Cristiani (1996) finds  $\xi$  of 0.2 and 0.6 for weak and strong lines respectively. The amplitude of the two point correlation function thus increases with decreasing redshift which is expected

in models with hierarchical clustering. We have studied the correlation of lines, excluding the lines deblended from the heavy element lines (marked 'd' in Table 1). The values of  $\xi$  are same as the values quoted above showing that of clustering found here is not due to the deblended lines from the heavy element lines.

Ostriker, Bajtlik and Duncan (1988) showed that the distribution function,  $P(x)$ , of line intervals scaled to the local mean,  $x$ , is a better tool for studying the clustering properties than the pair velocity correlation. They found a significant excess on the lower velocity scales in their low resolution sample. The observed line interval distribution and the expected distribution for the Poisson distribution of number of clouds along the line of sight, for the extended sample are given in figure 6. It is clear from the figure that there is an excess for small interline spacings over the expected value. The excess seems to be more for strong lines, confirming our pair velocity correlation results. However KS-test shows the probability of the maximum difference between the observed and the predicted distribution to occur by chance is 0.33 and 0.18 for low and high column density cutoffs respectively. Thus, in spite of a small excess in the first bin, the distribution is consistent with the poissonian expectations.

## 6 CONCLUSIONS

We have extracted a clean sample of Lyman alpha forest lines, free from contamination by heavy element line systems, from the spectra of B2 1225+317, taken at a resolution of  $18 \text{ km s}^{-1}$ . Lyman alpha forest lines blended with heavy element lines falling inside the forest have been deblended whenever possible and included in the sample. The sample consists of lines with redshifts between 1.7 and 2.2. The results of the analysis of the statistical properties of this sample can be summarized as follows.

1. The average velocity dispersion parameter of the sample is  $29.4 \pm 7.9 \text{ km s}^{-1}$ . 19 % of the lines have  $b$  values below  $20 \text{ km s}^{-1}$ . Low  $b$  values are more common among weak lines, 44 % of lines with  $\log N_{\text{HI}} < 13.5$  and 8% of lines with  $\log N_{\text{HI}} > 13.5$  have  $b < 20 \text{ km s}^{-1}$ .
2. A single powerlaw does not give an acceptable fit to the column density distribution for  $\log N_{\text{HI}} \geq 13.2$ . For  $\log N_{\text{HI}} \geq 13.4$ , a single power law is acceptable, the slope of the distribution, however, increases with increasing minimum column density cutoff, indicating a steepening or break in the power law. A double power law is fitted to the extended sample of lines, obtained by combining lines observed towards Q1331+170, Q1101-26 and Q2206-199. The slopes for  $\log N_{\text{HI}} \leq 14.0$  and  $\geq 14.0$  are -1.15 and -2.05 respectively.
3. We find evidence for  $N_{\text{HI}} - b$  correlation, it being significant up to  $3.2 \sigma$  level. The correlation is, however, mainly due to the narrow ( $b \leq 20 \text{ km s}^{-1}$ ) lines. Exclusion of these lines weakens the correlation to  $1.25 \sigma$ .
4. We find excess of line pairs with velocity splitting smaller than  $100 \text{ km s}^{-1}$ , the correlation coefficient being  $1.35 \pm 0.42$  and  $3.14 \pm 1.19$  for lines with  $\log N_{\text{HI}} \geq 13.2$  and  $\geq 13.7$  respectively.
5. The interline spacing distribution function shows an excess over small interline spacings; the excess, however, is not

found statistically significant, the probability of it's occurring by chance being 0.33.

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## Figure Captions

**Figure 1.** The observed spectrum of B2 1225+317 for 3278-3942 Å normalized to unit continuum. The profile fits are shown by continuous lines. Profiles of heavy element lines blended with forest lines are shown as dash-dot lines. Line components are indicated by tick marks.

**Figure 2.** The plot of  $\log N_{\text{H I}}$  vs  $b$ . The continuous line indicates the completeness limit of our sample. Crosses represent lines with  $\lambda \geq 3400 \text{ Å}$ . Starred triangles represent lines with  $\lambda \leq 3400 \text{ Å}$ .

**Figure 3.** Column density distribution for the extended sample. The best fit double power law is also shown. The slopes being -1.15 and -2.05 for  $\log N_{\text{H I}} \leq 14.0$  and  $\geq 14.0$  respectively.

**Figure 4.** Histogramme of velocity dispersion parameters ( $b$ -values) of the Lyman alpha forest lines in Q1225+317. Solid line is for sample S1, dashed line is for LWUPs and dotted line is for all the lines with  $\lambda \geq 3400 \text{ Å}$ , excluding LWUPs.

**Figure 5.** Velocity-pair histogramme for the extended sample. The expected number of pairs as well as the  $\pm 2\sigma$  values are shown by dashed lines. The upper panel is for lines with  $\log N_{\text{H I}} \geq 13.2$  while the lower panel is for lines with  $\log N_{\text{H I}} \geq 13.7$ .

**Figure 6.** The observed line interval distribution in the extended sample. The expected distribution for Poissonian distribution of clouds is shown by continuous line. The upper panel is for lines with  $\log N_{\text{H I}} \geq 13.2$ , while the lower panel is for lines with  $\log N_{\text{H I}} \geq 13.7$ .

**Table 1.** Profile fitting results

$\lambda$	$\log N(X)$	$b$ (km s <sup>-1</sup> )	$z$	ID, X	Remarks
3285.432	13.529 $\pm$ 0.06	22.09 $\pm$ 3.85	1.70257	H I 1215	Po F-Si IV $\lambda$ 1396
3286.182	13.410 $\pm$ 0.07	15.88 $\pm$ 4.09	1.70319	H I 1215	Po F-Si IV $\lambda$ 1396
3287.105	13.626 $\pm$ 0.05	32.39 $\pm$ 5.07	1.70394	H I 1215	Po F-Si IV $\lambda$ 1396
3299.263	14.565 $\pm$ 0.08	17.91 $\pm$ 0.67	1.71395	H I 1215	
3299.985	14.117 $\pm$ 0.04	26.89 $\pm$ 1.58	1.71454	H I 1215	
3300.800	13.526 $\pm$ 0.03	22.30 $\pm$ 2.56	1.71521	H I 1215	
3302.017	13.294 $\pm$ 0.03	28.62 $\pm$ 2.92	1.71621	H I 1215	
3305.787b	13.223 $\pm$ 0.08	42.71 $\pm$ 12.01	1.71931	H I 1215	
3306.614	13.290 $\pm$ 0.06	21.17 $\pm$ 4.18	1.71999	H I 1215	Po F-Si IV $\lambda$ 1402
3307.411	13.456 $\pm$ 0.14	9.14 $\pm$ 3.73	1.72065	H I 1215	Po F-Si IV $\lambda$ 1402
3308.402	13.449 $\pm$ 0.03	37.49 $\pm$ 3.96	1.72146	H I 1215	Po F-Si IV $\lambda$ 1402, Co B-Si II $\lambda$ 1260
3316.489	14.305 $\pm$ 0.06	32.53 $\pm$ 2.98	1.72812	H I 1215	
3317.363	13.735 $\pm$ 0.19	30.14 $\pm$ 17.18	1.72884	H I 1215	
3317.838	13.609 $\pm$ 0.19	18.09 $\pm$ 5.46	1.72923	H I 1215	
3318.684	13.830 $\pm$ 0.02	31.79 $\pm$ 1.99	1.72992	H I 1215	
3325.052d	13.654 $\pm$ 0.04	36.95 $\pm$ 13.38	1.73516	H I 1215	
3325.685	13.776 $\pm$ 0.05	31.92 $\pm$ 4.53	1.79372	Si II 1190	
3326.162	13.228 $\pm$ 0.18	11.33 $\pm$ 9.8	1.79412	Si II 1190	
3326.901	13.929 $\pm$ 0.09	13.74 $\pm$ 2.62	1.79474	Si II 1190	
3327.151	13.262 $\pm$ 0.22	10.71 $\pm$ 8.89	1.79495	Si II 1190	
3327.488	13.068 $\pm$ 0.27	8.93 $\pm$ 7.77	1.79523	Si II 1190	
3327.917	12.964 $\pm$ 0.71	21.89 $\pm$ 13.78	1.79559	Si II 1190	
3328.531	12.442 $\pm$ 0.12	15.56 $\pm$ 27.95	1.79611	Si II 1190	
3333.714	13.776 $\pm$ 0.05	31.92 $\pm$ 4.53	1.79372	Si II 1193	
3334.192	13.228 $\pm$ 0.18	11.33 $\pm$ 9.8	1.79412	Si II 1193	
3334.933	13.929 $\pm$ 0.09	13.74 $\pm$ 2.62	1.79474	Si II 1193	
3335.184	13.262 $\pm$ 0.22	10.71 $\pm$ 8.89	1.79495	Si II 1193	
3335.521	13.068 $\pm$ 0.27	8.93 $\pm$ 7.77	1.79523	Si II 1193	
3335.951	12.964 $\pm$ 0.71	21.89 $\pm$ 13.78	1.79559	Si II 1193	
3336.566	12.442 $\pm$ 0.12	15.56 $\pm$ 27.95	1.79611	Si II 1193	
3338.096b	13.599 $\pm$ 0.13	103.54 $\pm$ 45.77	1.74589	H I 1215	
3347.052s	13.555 $\pm$ 0.04	23.69 $\pm$ 2.53	1.75326	H I 1215	
3348.434s	13.665 $\pm$ 0.04	28.67 $\pm$ 2.59	1.75439	H I 1215	
3350.560	13.569 $\pm$ 0.03	31.76 $\pm$ 3.26	1.75614	H I 1215	
3351.220	13.760 $\pm$ 0.16	10.36 $\pm$ 3.13	1.75669	H I 1215	
3351.785	13.830 $\pm$ 0.04	28.62 $\pm$ 4.21	1.75715	H I 1215	
3352.324	13.230 $\pm$ 0.07	37.60 $\pm$ 8.50	1.75759	H I 1215	
3356.996s	13.958 $\pm$ 0.02	28.30 $\pm$ 0.95	1.76144	H I 1215	
3370.170	13.658 $\pm$ 0.10	17.65 $\pm$ 0.01	1.79334	Si III 1206	
3370.677	13.068 $\pm$ 0.15	15.00 $\pm$ 0.03	1.79377	Si III 1206	
3371.046	13.839 $\pm$ 0.40	13.00 $\pm$ 1.94	1.79407	Si III 1206	
3371.852	13.719 $\pm$ 0.09	29.27 $\pm$ 6.24	1.79474	Si III 1206	
3372.446	15.618 $\pm$ 0.17	4.36 $\pm$ 9.08	1.79523	Si III 1206	
3372.882	12.559 $\pm$ 0.13	15.38 $\pm$ 9.26	1.79559	Si III 1206	
3373.253	12.562 $\pm$ 0.10	8.59 $\pm$ 13.18	1.79590	Si III 1206	
3373.671	12.480 $\pm$ 0.09	13.77 $\pm$ 16.61	1.79625	Si III 1206	
3382.200b	13.493 $\pm$ 0.06	109.74 $\pm$ 20.84	1.78217	H I 1215	
3384.814s	13.318 $\pm$ 0.05	19.36 $\pm$ 3.54	1.78432	H I 1215	
3392.583b	14.279 $\pm$ 0.05	43.05 $\pm$ 2.95	1.79071	H I 1215	
3393.472b	14.241 $\pm$ 0.41	12.73 $\pm$ 4.94	1.79144	H I 1215	
3394.502b	13.611 $\pm$ 0.05	36.35 $\pm$ 5.19	1.79229	H I 1215	
3395.345	14.655 $\pm$ 0.32	23.73 $\pm$ 5.75	1.79298	A H I 1215	
3396.222	14.975 $\pm$ 0.26	10.00 $\pm$ 0.00	1.79370	A H I 1215	
3396.722	15.446 $\pm$ 0.46	10.00 $\pm$ 0.00	1.79412	A H I 1215	
3397.422	17.386 $\pm$ 0.32	10.00 $\pm$ 0.00	1.79469	A H I 1215	
3397.702	11.938 $\pm$ 3.40	10.00 $\pm$ 0.00	1.79492	A H I 1215	
3398.062	16.394 $\pm$ 0.79	10.00 $\pm$ 0.00	1.79522	A H I 1215	
3398.552	13.447 $\pm$ 0.55	10.00 $\pm$ 0.00	1.79562	A H I 1215	
3399.152	18.364 $\pm$ 0.09	10.00 $\pm$ 0.00	1.79611	A H I 1215	
3400.564	16.583 $\pm$ 0.52	7.81 $\pm$ 0.41	1.79728	A H I 1215	
3401.172	13.447 $\pm$ 0.16	13.95 $\pm$ 3.40	1.79778	A H I 1215	



$\lambda$	$\log N(X)$	$b \text{ (km s}^{-1}\text{)}$	$z$	ID, X	Remarks
3414.694s	$13.684 \pm 0.03$	$27.86 \pm 1.79$	1.80890	H I 1215	*
3430.562	$14.301 \pm 0.06$	$34.63 \pm 4.15$	1.82195	H I 1215	*
3431.239	$13.914 \pm 0.10$	$78.55 \pm 11.06$	1.82251	H I 1215	*
3432.236	$12.969 \pm 0.10$	$6.45 \pm 5.73$	1.82333	H I 1215	
3432.766	$13.418 \pm 0.05$	$33.39 \pm 4.21$	1.82376	H I 1215	*
3443.481	$13.161 \pm 0.09$	$19.42 \pm 6.71$	1.83258	H I 1215	
3444.282	$13.879 \pm 0.06$	$25.89 \pm 3.30$	1.83324	H I 1215	*
3445.317	$13.592 \pm 0.10$	$21.24 \pm 8.02$	1.22538	C IV 1548	
3449.274	$13.650 \pm 0.07$	$19.17 \pm 3.32$	1.83734	H I 1215	*
3449.827	$13.158 \pm 0.10$	$38.70 \pm 3.51$	1.83780	H I 1215	
3451.048	$13.592 \pm 0.04$	$21.24 \pm 3.51$	1.22538	C IV 1550	
3454.151s	$13.217 \pm 0.05$	$18.16 \pm 2.82$	1.84136	H I 1215	*
3454.964s	$13.364 \pm 0.04$	$17.08 \pm 2.01$	1.84202	H I 1215	*
3458.571s	$13.344 \pm 0.03$	$31.05 \pm 3.03$	1.84499	H I 1215	*
3462.256	$13.785 \pm 0.05$	$16.12 \pm 2.68$	1.79480	N V 1238	
3462.875d	$13.549 \pm 0.04$	$33.16 \pm 3.84$	1.84853	H I 1215	*
3465.643s	$13.013 \pm 0.05$	$16.73 \pm 3.62$	1.85081	H I 1215	
3473.377	$13.785 \pm 0.05$	$16.12 \pm 2.68$	1.79480	N V 1238	
3478.466s	$13.498 \pm 0.02$	$21.98 \pm 0.98$	1.86136	H I 1215	*
3499.087s	$13.111 \pm 0.03$	$19.84 \pm 1.83$	1.87832	H I 1215	
3503.030	$13.121 \pm 0.06$	$41.76 \pm 7.37$	1.88156	H I 1215	Po B-C II $\lambda$ 1334
3503.752	$12.924 \pm 0.06$	$14.67 \pm 3.41$	1.88216	H I 1215	Po B-C II $\lambda$ 1334
3507.435	$17.389 \pm 0.17$	$7.77 \pm 0.18$	1.88519	C H I 1215	
3508.325	$14.310 \pm 0.20$	$60.82 \pm 36.56$	1.88592	C H I 1215	
3508.903	$13.977 \pm 1.36$	$6.57 \pm 36.44$	1.88639	C H I 1215	
3509.399	$14.000 \pm 0.18$	$32.30 \pm 5.91$	1.88680	C H I 1215	
3511.933b	$13.986 \pm 0.02$	$105.74 \pm 7.01$	1.88889	C H I 1215	
3518.631s	$13.728 \pm 0.01$	$22.30 \pm 0.58$	1.89440	H I 1215	*
3519.643	$13.947 \pm 0.03$	$14.51 \pm 0.64$	1.89523	D H I 1215	
3520.064	$13.857 \pm 0.08$	$14.47 \pm 3.57$	1.89558	D H I 1215	
3520.643	$14.515 \pm 0.10$	$21.32 \pm 2.28$	1.89605	D H I 1215	
3521.572	$13.776 \pm 0.05$	$31.92 \pm 5.36$	1.79372	Si II 1260	
3522.078	$13.228 \pm 0.10$	$11.33 \pm 2.02$	1.79412	Si II 1260	
3522.860	$13.929 \pm 0.04$	$13.74 \pm 0.48$	1.79474	Si II 1260	
3523.125	$13.262 \pm 0.07$	$10.71 \pm 1.43$	1.79495	Si II 1260	
3523.481	$13.068 \pm 0.05$	$8.93 \pm 1.23$	1.79523	Si II 1260	
3523.936	$12.964 \pm 0.03$	$21.89 \pm 1.70$	1.79559	Si II 1260	
3524.586	$12.442 \pm 0.05$	$15.56 \pm 2.83$	1.79611	Si II 1260	
3532.849	$14.061 \pm 0.03$	$38.37 \pm 2.38$	1.90609	H I 1215	*
3533.448	$13.407 \pm 0.12$	$8.43 \pm 5.72$	1.90658	H I 1215	*
3533.925	$13.942 \pm 0.04$	$25.77 \pm 2.23$	1.90698	H I 1215	*
3543.849s	$13.422 \pm 0.03$	$44.72 \pm 4.68$	1.91514	H I 1215	*
3548.555s	$13.104 \pm 0.02$	$13.96 \pm 1.34$	1.91901	H I 1215	PC H-Fe II $\lambda$ 2600
3553.827s	$13.188 \pm 0.07$	$27.78 \pm 6.74$	1.92335	H I 1215	
3570.644s	$13.626 \pm 0.02$	$27.33 \pm 1.41$	1.93718	H I 1215	*
3573.287s	$13.588 \pm 0.01$	$23.44 \pm 0.76$	1.93936	H I 1215	*
3574.467s	$12.889 \pm 0.02$	$16.15 \pm 1.28$	1.94033	H I 1215	
3577.160b	$13.009 \pm 0.06$	$27.06 \pm 6.32$	1.94254	H I 1215	
3596.782	$13.093 \pm 0.04$	$22.00 \pm 3.41$	1.95868	H I 1215	
3597.538	$13.258 \pm 0.03$	$19.89 \pm 2.30$	1.95930	H I 1215	*
3604.661	$14.581 \pm 0.06$	$34.42 \pm 1.35$	1.96516	H I 1215	*
3605.735	$13.137 \pm 0.04$	$7.90 \pm 1.54$	1.96605	H I 1215	
3607.005b	$13.199 \pm 0.08$	$44.66 \pm 13.07$	1.96709	H I 1215	
3611.744s	$12.884 \pm 0.06$	$15.25 \pm 3.65$	1.97099	H I 1215	
3617.934s	$13.927 \pm 0.01$	$35.06 \pm 0.95$	1.97608	H I 1215	*
3621.071	$13.161 \pm 0.03$	$12.42 \pm 1.70$	1.97866	H I 1215	
3621.701	$13.913 \pm 0.02$	$25.50 \pm 1.47$	1.97918	H I 1215	*
3622.341	$13.688 \pm 0.03$	$18.18 \pm 1.82$	1.97971	H I 1215	*
3622.896	$13.720 \pm 0.03$	$22.11 \pm 1.71$	1.98016	H I 1215	*
3624.112b	$13.885 \pm 0.03$	$72.80 \pm 5.84$	1.98116	H I 1215	?
3625.667	$14.250 \pm 0.02$	$46.14 \pm 1.17$	1.98244	H I 1215	*
3633.688s	$13.378 \pm 0.03$	$18.74 \pm 2.00$	1.98904	H I 1215	*

$\lambda$	$\log N(X)$	$b \text{ (km s}^{-1}\text{)}$	$z$	ID, X	Remarks
3637.900	$14.396 \pm 0.05$	$23.50 \pm 2.16$	1.79373	O I 1302	
3638.136d	$13.584 \pm 0.07$	$14.73 \pm 4.82$	1.99270	H I 1215	*
3638.423	$13.766 \pm 0.12$	$9.73 \pm 3.47$	1.79413	O I 1302	
3641.228	$14.288 \pm 0.05$	$27.46 \pm 1.82$	1.99524	H I 1215	*
3641.864	$13.326 \pm 0.14$	$22.41 \pm 5.21$	1.99577	H I 1215	*
3644.041	$13.776 \pm 0.05$	$31.92 \pm 4.53$	1.79372	Si II 1304	
3644.380d	$13.544 \pm 0.05$	$24.18 \pm 1.92$	1.99784	H I 1215	*
3644.563	$13.228 \pm 0.18$	$11.33 \pm 9.83$	1.79412	Si II 1304	
3645.373	$13.929 \pm 0.09$	$13.74 \pm 2.62$	1.79474	Si II 1304	
3645.460d	$13.428 \pm 0.06$	$37.60 \pm 4.35$	1.99872	H I 1215	*
3645.648	$13.262 \pm 0.22$	$10.71 \pm 8.89$	1.79495	Si II 1304	
3646.016	$13.068 \pm 0.27$	$8.93 \pm 7.77$	1.79523	Si II 1304	
3646.486	$12.964 \pm 0.71$	$21.89 \pm 13.78$	1.79559	Si II 1304	
3647.159	$12.442 \pm 0.12$	$15.56 \pm 27.95$	1.79611	Si II 1304	
3651.995s	$13.975 \pm 0.03$	$28.87 \pm 1.05$	2.00410	H I 1215	*
3657.067s	$13.025 \pm 0.02$	$20.20 \pm 1.59$	2.00827	H I 1215	
3659.730b	$13.100 \pm 0.05$	$44.37 \pm 7.69$	2.01046	H I 1215	
3662.339	$13.561 \pm 0.11$	$23.72 \pm 3.50$	2.01261	H I 1215	*
3662.890	$13.750 \pm 0.08$	$33.38 \pm 4.49$	2.01306	H I 1215	*
3670.743	$13.037 \pm 0.23$	$33.11 \pm 16.06$	2.01952	H I 1215	
3671.432	$13.999 \pm 0.04$	$26.99 \pm 1.93$	2.02009	H I 1215	*
3674.240s	$13.185 \pm 0.02$	$20.09 \pm 1.23$	2.02240	H I 1215	
3676.134s	$13.739 \pm 0.02$	$30.65 \pm 1.73$	2.02396	H I 1215	*
3680.083	$13.217 \pm 0.03$	$38.02 \pm 3.53$	2.02721	H I 1215	*
3681.644	$14.328 \pm 0.03$	$41.88 \pm 1.13$	2.02849	H I 1215	*
3688.010s	$12.988 \pm 0.03$	$27.99 \pm 2.79$	2.03373	H I 1215	
3697.779s	$14.009 \pm 0.01$	$36.28 \pm 0.67$	2.04176	H I 1215	*
3701.355	$13.146 \pm 0.09$	$19.05 \pm 3.71$	2.04470	H I 1215	
3701.994	$14.041 \pm 0.02$	$26.51 \pm 1.37$	2.04523	H I 1215	*
3703.485b	$12.973 \pm 0.05$	$41.65 \pm 7.27$	2.04646	H I 1215	
3709.109	$13.648 \pm 0.08$	$35.40 \pm 4.84$	2.05108	H I 1215	*
3710.044	$13.494 \pm 0.14$	$42.77 \pm 17.45$	2.05185	H I 1215	*
3710.669	$12.808 \pm 0.19$	$9.84 \pm 7.22$	2.05237	H I 1215	
3712.725b	$13.143 \pm 0.07$	$77.65 \pm 17.94$	2.05406	H I 1215	
3723.698	$12.948 \pm 0.04$	$15.72 \pm 2.23$	2.06308	H I 1215	
3725.157b	$13.255 \pm 0.03$	$66.35 \pm 7.13$	2.06428	H I 1215	?
3727.675	$14.124 \pm 0.02$	$22.89 \pm 1.07$	1.79324	C II 1334	
3727.989	$14.270 \pm 0.04$	$21.38 \pm 2.15$	1.79348	C II 1334	
3728.671	$14.754 \pm 0.03$	$24.36 \pm 0.83$	1.79399	C II 1334	
3729.403	$14.210 \pm 0.04$	$9.36 \pm 0.81$	1.79454	C II 1334	
3729.899	$16.193 \pm 0.09$	$8.95 \pm 0.31$	1.79491	C II 1334	
3730.348	$14.182 \pm 0.03$	$16.92 \pm 1.31$	1.79525	C II 1334	
3730.836	$13.957 \pm 0.02$	$16.23 \pm 1.08$	1.79561	C II 1334	
3731.344	$13.477 \pm 0.03$	$9.53 \pm 1.65$	1.79599	C II 1334	
3739.857s	$12.920 \pm 0.05$	$22.11 \pm 4.07$	2.07638	H I 1215	
3742.297s	$13.396 \pm 0.03$	$22.72 \pm 2.08$	2.07838	H I 1215	*
3743.280s	$13.632 \pm 0.01$	$24.23 \pm 0.61$	2.07919	H I 1215	*
3745.524b	$14.190 \pm 0.03$	$32.30 \pm 1.79$	2.08104	H I 1215	?
3746.846b	$14.068 \pm 0.02$	$39.09 \pm 1.97$	2.08212	H I 1215	?
3751.727b	$13.364 \pm 0.03$	$46.03 \pm 4.59$	2.08614	H I 1215	?
3756.656b	$13.548 \pm 0.03$	$53.98 \pm 4.78$	2.09019	H I 1215	?
3758.338s	$13.207 \pm 0.02$	$18.35 \pm 1.24$	2.09158	H I 1215	PC C-O I $\lambda$ 1302
3759.390	$13.615 \pm 0.03$	$18.07 \pm 1.94$	1.42824	C IV 1548	Po C-O I $\lambda$ 1302
3760.124	$13.790 \pm 0.03$	$15.50 \pm 1.59$	1.42871	C IV 1548	
3760.585	$13.204 \pm 0.07$	$16.61 \pm 4.35$	1.42901	C IV 1548	
3763.183s	$13.386 \pm 0.04$	$15.24 \pm 1.88$	2.09556	H I 1215	*
3765.643	$13.615 \pm 0.03$	$18.07 \pm 1.94$	1.42824	C IV 1550	
3766.378	$13.790 \pm 0.03$	$15.50 \pm 1.59$	1.42871	C IV 1550	
3766.840	$13.204 \pm 0.07$	$16.61 \pm 4.35$	1.42901	C IV 1550	
3771.969s	$13.701 \pm 0.02$	$33.49 \pm 1.87$	2.10279	H I 1215	*
3776.511s	$12.912 \pm 0.03$	$5.35 \pm 0.82$	2.10653	H I 1215	
3779.612s	$13.878 \pm 0.01$	$41.34 \pm 0.99$	2.10908	H I 1215	*

$\lambda$	$\log N(X)$	$b \text{ (km s}^{-1}\text{)}$	$z$	ID, X	Remarks
3790.585	$13.571 \pm 0.11$	$24.49 \pm 6.56$	2.11810	G H I 1215	
3791.145	$14.498 \pm 0.03$	$57.69 \pm 2.62$	2.11856	G H I 1215	
3792.781	$14.642 \pm 0.10$	$33.69 \pm 2.01$	2.11991	G H I 1215	
3799.107	$13.591 \pm 0.01$	$31.75 \pm 0.98$	2.12511	H I 1215	*
3799.942	$12.960 \pm 0.03$	$16.92 \pm 1.66$	2.12580	H I 1215	
3802.694s	$13.676 \pm 0.02$	$37.39 \pm 1.60$	2.12806	H I 1215	*
3805.392b	$13.068 \pm 0.06$	$37.69 \pm 6.85$	2.13028	H I 1215	
3808.647s	$12.897 \pm 0.03$	$14.69 \pm 2.02$	2.13296	H I 1215	
3811.431d	$15.072 \pm 0.24$	$31.64 \pm 3.83$	2.13525	H I 1215	*
3811.525	$13.481 \pm 0.03$	$52.37 \pm 2.80$	0.36303	Mg II 2796	
3812.014	$13.759 \pm 0.04$	$26.60 \pm 1.24$	0.36321	Mg II 2796	
3817.186	$13.100 \pm 0.04$	$31.83 \pm 4.03$	2.13998	H I 1215	
3821.311	$13.481 \pm 0.03$	$52.37 \pm 2.80$	0.36303	Mg II 2803	
3821.800	$13.759 \pm 0.04$	$26.60 \pm 1.24$	0.36321	Mg II 2803	
3822.672d	$13.900 \pm 0.02$	$30.41 \pm 1.47$	2.14450	H I 1215	*
3826.475s	$12.733 \pm 0.03$	$18.45 \pm 2.41$	2.14763	H I 1215	
3834.612s	$12.934 \pm 0.05$	$16.86 \pm 3.07$	2.15432	H I 1215	
3838.264b	$12.971 \pm 0.07$	$40.36 \pm 8.93$	2.15732	H I 1215	
3839.764b	$13.057 \pm 0.10$	$49.57 \pm 15.76$	2.15856	H I 1215	
3844.764b	$13.305 \pm 0.04$	$55.13 \pm 5.47$	2.16267	H I 1215	?
3850.580s	$12.843 \pm 0.06$	$20.94 \pm 4.55$	2.16745	H I 1215	PC C-C II $\lambda 1334$
3852.793b	$13.220 \pm 0.04$	$51.98 \pm 6.72$	2.16928	H I 1215	? PC C-C II $\lambda 1334$
3857.335	$13.013 \pm 0.03$	$9.84 \pm 1.88$	2.17301	H I 1215	
3858.039	$13.049 \pm 0.04$	$24.85 \pm 3.03$	2.17359	H I 1215	
3863.990b	$13.204 \pm 0.16$	$94.36 \pm 47.07$	2.17849	H I 1215	? PC D-C II $\lambda 1334$ & G-N V $\lambda 1238$
3865.848b	$13.068 \pm 0.06$	$50.91 \pm 9.74$	2.18001	H I 1215	PC D-C II $\lambda 1334$ & G-N V $\lambda 1238$
3890.501s	$13.009 \pm 0.03$	$8.85 \pm 1.72$	2.20029	H I 1215	
3893.178	$13.158 \pm 0.08$	$12.40 \pm 3.44$	1.79330	Si IV 1393	
3893.888	$13.885 \pm 0.14$	$24.81 \pm 14.81$	1.79381	Si IV 1393	
3894.166d	$14.522 \pm 0.13$	$35.61 \pm 10.73$	2.20331	H I 1215	
3894.351	$13.274 \pm 2.11$	$6.54 \pm 38.13$	1.79414	Si IV 1393	
3895.073	$13.769 \pm 0.15$	$10.66 \pm 7.01$	1.79466	Si IV 1393	
3895.488	$14.076 \pm 0.20$	$17.40 \pm 4.80$	1.79496	Si IV 1393	
3895.970d	$13.725 \pm 0.16$	$7.80 \pm 2.89$	2.20479	H I 1215	
3896.307	$13.342 \pm 0.08$	$20.45 \pm 3.54$	1.79555	Si IV 1393	
3897.053	$13.004 \pm 0.08$	$23.73 \pm 3.27$	1.79608	Si IV 1393	
3900.517s	$13.064 \pm 0.04$	$23.20 \pm 3.47$	2.20853	H I 1215	
3905.918b	$13.086 \pm 0.06$	$64.02 \pm 12.06$	2.21298	H I 1215	
3907.887b	$13.053 \pm 0.06$	$36.65 \pm 6.68$	2.21460	H I 1215	
3916.103b	$12.827 \pm 0.06$	$44.20 \pm 9.30$	2.22135	H I 1215	
3918.360	$13.158 \pm 0.08$	$12.40 \pm 3.44$	1.79330	Si IV 1402	
3919.074	$13.885 \pm 0.14$	$24.81 \pm 14.81$	1.79381	Si IV 1402	
3919.541	$13.274 \pm 2.11$	$6.54 \pm 38.13$	1.79414	Si IV 1402	
3920.267	$13.769 \pm 0.15$	$10.66 \pm 7.01$	1.79466	Si IV 1402	
3920.685	$14.076 \pm 0.20$	$17.40 \pm 4.80$	1.79496	Si IV 1402	
3921.509	$13.342 \pm 0.08$	$20.45 \pm 3.54$	1.79555	Si IV 1402	
3922.259	$13.004 \pm 0.08$	$23.73 \pm 3.27$	1.79608	Si IV 1402	
3938.544s	$13.158 \pm 0.04$	$30.21 \pm 4.01$	2.23981	H I 1215	

b Line shape is not proper, probably because of blends or bad pixel

s Lines fitted with single components

d Lyman alpha forest lines which are deblended from metal lines

\* Lines included in the Lyman alpha line sample

? Lines that can be included in the Lyman alpha line sample but for their 'unusual' shape

Po Possibly

Co Contaminated by

PC Possibly contaminated by

**Table 2.** Column density distribution

QSO	$\log N_{\text{H I}}^{\text{min}}$	No.of Lines	$\beta$	$\langle z \rangle$	$P_{\text{ks}}$
B2 1225+317	13.2	52	$1.828 \pm 0.115$	1.9768	0.088
	13.4	42	$2.025 \pm 0.158$	1.9768	0.337
	13.6	30	$2.241 \pm 0.226$	1.9851	0.526
	13.8	18	$2.334 \pm 0.314$	1.9843	0.387
	14.0	9	$2.333 \pm 0.444$	1.9912	0.854
B2 1225+317	13.2	190	$1.742 \pm 0.054$	2.0195	0.039
Q1331+170	13.4	147	$1.829 \pm 0.068$	2.0226	0.113
Q1101-26	13.6	110	$1.938 \pm 0.089$	2.0304	0.174
&	13.8	80	$2.080 \pm 0.121$	2.0444	0.575
Q2206-199	14.0	45	$2.014 \pm 0.151$	2.0470	0.685